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ABSTRACT

Described are 12 instruments utilized in studies measuring the Piagetian level of cognitive development of students. Instruments for elementary and secondary students are included, and a detailed analysis of the concepts measured and the method for evaluating the results of each instrument is included. Stressed is the importance of analyzing why a particular response is obtained rather than scoring the answers obtained. (SL)

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OPPORTUNITES FOR CONCRETE AND FORMAL THINKING ON SCIENCE TASKS

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Since science as process of inquiry makes demands on the reasoning ability of practitioners, science teaching makes such demands of students. I have found it interesting to examine science activities at various levels and in various scientific fields, with the intention of identifying the type of reasoning that may occur. Consider the example in Fig. 1, for instance, used with eight and nine-year old children in the SCIS program.[1] The students are to set up experiments that correspond to the pictured systems, thus translating these representations into reality. Because of the simple and direct correspondence of the pictures and the materials, I concluded that this task requires concrete thought. I imagine that a formal thinker would be impatient with this activity. Compare, now, another experimental activity (Fig. 2) used with eleven to twelve year olds.[2] In part B on this page, the students are invited to set up experiments, but this time they have to select the procedure and materials themselves, with only the instruction to "investigate variables." The lack of specific instructions, the need to consider alternatives and their relationship, led me to conclude that this task invites formal reasoning. It requires the student to accept lack of immediate closure[3] since several experiments must be carried out before a pattern emerges. This task is an optional activity in the SCIS program, a challenge to above-average sixth graders. The activity outlined in Fig. 1 and in part A of Fig. 2 provides closure as soon the student fulfills the explicit requirements of the task, a characteristic of concrete reasoning.

The two examples I have given were concerned with experimental investigations. Theoretical activities--so-called "brain teasers"--can also be roughly classified in the same way. Thus, the example shown in Fig. 3 requires conservation of length and seriation:[4] many small steps are equivalent to fewer large steps. The children tackle this problem after they measure distances by pacing. In my opinion, this is an example of concrete thought, since a quantitative analysis of the exact length of Bill's paces is not required. Still, the inverse relationship of number and size of paces suggests a little more than the simplest kind of seriation. Appropriately, this brain teaser is intended for nine- and ten-year-olds in the SCIS program. Notice that the solution may involve hypothetico-deductive reasoning, along these lines: if the steps are longer, as in A, then the larger number of steps will cover a greater distance; if the steps are shorter, as in C, then the larger number of steps may cover the same distance. Since the hypotheses are given by the answer choices and are not generated by the student, I believe that they do not reflect formal reasoning.

The example in Fig. 4 is used after the students have worked with a small plastic syringe at various angles to pop a rubber stopper in freely exploratory activities and in a guided investigation of the effect of varying the launch angle.[5] The second question can be answered concretely from the observations remembered by the children--using merely the idea of reproducibility of data

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and focussing on the angle variable only. Or, the students may reason about both the angle and stopper depth variables, whose effects partly compensate in C and D. This would be applying formal thought. On the first question, the crux is that, whereas the flight distance is the observable outcome of the experiments, the energy imparted to the stopper is an abstraction that must be inferred by comparing the speed and force with which the stopper is launched regardless of the angle. Actually, the depth to which the stopper is inserted into the syringe barrel is the most important determinant of the energy transfer, and most children discover this relationship. Still, the need to distinguish the observed flight distance from the non-observable energy transfer makes me classify this task as requiring formal thought.

Before extending my discussion of science activities to the secondary level, I should like to point out that I have spoken from a theoretical viewpoint. I have used certain criteria to identify the operational opportunities in the activities. Generally speaking, concrete approaches consisted of seriation, one-to-one correspondence, conservation, transitivity, and class inclusion applied to real objects or to symbols representing them. If the subject formulated and tested hypotheses, used symbols that did not correspond directly to real objects, used a functional relationship quantitatively, planned a series of interdependent steps that covered all available alternatives, considered a general case instead of specific instances, or accepted lack of closure in other ways, then I concluded that he applied formal thought.

The question arises, how does the performance of students on science tasks in school relate to their developmental level as determined by standard Piagetian tasks? This matter is being investigated by Anton E. Lawson working with John W. Renner at the University of Oklahoma in Norman.[6] By using floating and sinking objects, conservation of volume, and the balance beam, Lawson is seeking to identify the developmental level of a large group of secondary school students. He has prepared tests in biology, chemistry, and physics, whose content is appropriate to the respective high school courses, and whose questions have been classified by him and several others according to their operational level. By comparing the students' responses on the questions with the students' developmental level, Lawson hopes to find how reliable the classification of the questions was and what opportunities for logical operations arise in these courses. I might add that the reviewers of the questions did not agree on all items, partly because the students' unknown educational experience was expected to influence their responses. Personality variables such as impulsiveness and anxiety also will affect the outcome of this study. In this kind of investigation, one may choose to examine three quite different problems: one is to identify the reasoning used by a particular individual in responding, successfully or unsuccessfully, to a particular task; the second is to predict the degree of success on the task that will be achieved by individuals who usually reason at a certain developmental level and have a specified background of instruction and/or experience; the third is to consider the latitude of a task--what range of logical operations is stimulated by it, and what range leads to success.

After this theoretical digression, I shall return to additional examination questions that were taken from teacher-made tests, college board practice questions,[7] and Lawson's work,[6] with some adaptation to make them more suitable for this presentation. In Fig. 5 are two biology questions dealing with heredity. The first of these involves crossing

heterozygous individuals with homozygous recessives and requires concrete thought, in my opinion. None of the biology books I examined actually presented this example, but they did present a technique for predicting the outcome by manipulating the symbols D and d that represent the alleles. Three-quarters of the forty-five high school students who responded to this question predicted a 50-50 division of the two genotypes Dd and dd. Some of these students drew the diagram I have indicated at the bottom of Fig. 5 to help them answer the question, thus giving evidence of a concrete approach.

The second question specified the distribution of alleles and can be solved by the same type of diagram, but only if ten alleles are indicated along each edge of the box: three A and seven a (see Fig. 5, bottom). By matching these in the square array, the relative frequencies of the three genotypes can be predicted. Even though this procedure appears to be a direct extension of the simple one used by many students, it differs in one significant respect: in the solution to problem I, the symbol Dd represents both the equal frequencies of the two alleles and the occurrence of alleles in each individual of one mating population; in the solution to II, the symbols A and a describe the relative frequencies of alleles in the population but have no connection to individual organisms (these may have genotypes AA, Aa, or aa). In case II, therefore, the symbolism is more abstract than in case I. Actually, two of the students stated the correct percentages, and one of them quoted the Hardy-Weinberg principle, which provides an algorithm that is applied in the students' text[8] to the case of 40% dominant allele. Of the remaining students, somewhat more than half quoted three percentages for the three genotypes, often using figures such that the dominant genotype or the dominant phenotype had a probability of 30%. The others provided partial answers. Unfortunately--and this was my mistake--I did not ask the students to explain their procedure.

I should like to inject another question here: what is the operational meaning of use of an algorithm, a standard, memorized procedure for generating a result? Does the fact that the algorithm is stated in formal terms mean that the user is necessarily applying formal thought? I think not, and would judge each instance individually.

I selected the next question as affording either concrete or formal thought (Fig. 6). It involves seriation with respect to a tangible relationship, that of one organism consuming another, but also brings into play the food-mineral cycle. Indeed, about three-fourths of the student group successfully selected alternative C, with most of the remainder choosing D; two were undecided. In all but a very few cases, however, the reason for eliminating an incorrect alternative was a single objection, such as "seeds don't eat sparrows," for A. This I took to be a concrete approach. Some responses, however, showed awareness of the mineral cycle and the similarity of C and D, and explained that seeds must be first because they initiate the food chain. This explanation indicates a formal operation.

My last example from biology is shown in Fig. 7. In my view, this requires formal thought, since a quantitative analysis is requested. Actually, three out of fifty-five students selected the correct answer E, but only one justified it by referring to the 25-fold enlargement of the field of view. A second one said the field would be larger without saying how much, and the third one stated only "80 x 50 = 4000/2 = 2000". To my surprise, four of the remaining students chose C, and, to my still

greater surprise, the other forty-eight students chose answers B and D in equal numbers! Many explanations included arithmetic operations only, but some added qualitative comments about the enlarged field of view when the individual cells appear smaller under low power. Others justified the smaller number in terms of the lower power, however. This observation reflects many students' tendency to suppress common sense (lower power means larger field) when confronted with mathematical tasks, a tendency I have observed all too frequently on other occasions.

I was surprised when I originally examined eight teacher-made biology tests and failed to locate any questions that, in my judgement, invited formal thought. Even on the college board examples,[7] it seemed to me that the wording of the questions in biology, rather than the applications of biological concepts, was used to make the questions more demanding. Clearly there are tasks that allow formal thought, such as the planning of experiments that involve the identification, separation, and control of variables. Or, the evaluation of the consequences of man's interference in the interlocking cycles in the ecosystem. In my efforts to make up examples, however, I found that these tasks, when stated verbally on a written test, lost most of their challenge, because all of the conditions have to be specified explicitly. In a laboratory or real life situation this would not be the case; and tracking down sources of error or inconsistencies among data can be exceedingly demanding in biology as well as in other fields. In my view, teachers should challenge their students without requiring that all perform on the same high level of reasoning.

Let me turn now to high school chemistry. Here I found problems requiring formal thought everywhere I looked. I had difficulty locating items that could be solved on the concrete level and did not depend on recall of facts concerning the properties of specific elements and compounds. The atomic theory, of course, is the main conceptual framework in chemistry, and affords ample opportunity for formal thought when chemical phenomena are being interpreted and explained. At the same time, as you will see, it has some aspects of a language that, once learned, can be applied in simple situations (e.g., conservation of atoms in a reaction) by the use of concrete operations. In many applications of atomic theory, proportional reasoning, an aspect of formal thought is exceedingly important. It occurs in applications of the ideal gas laws, the calculation of the ratios of reactants and reaction products, and the use of equilibrium constants. Other tasks requiring formal thought have to do with the application of energy conservation and energy transfer, where energy has to be discriminated from observables such as temperature and pressure (see also Fig. 4). Finally, there are problems of deductive logic, when data about precipitates, color of ions, and weight ratios have to be used to identify the reacting compounds. Since this last process requires a great deal of empirical information or chemical tables, I decided not to investigate it.

My first example relates to the use of chemical symbols to represent atoms (Fig. 8). Here the manipulation of symbols according to well-defined rules makes use of concrete thought. Seven of nine students counted the atoms successfully, one made a counting mistake, and the last omitted the three atoms in water. A second task involving chemical symbols is the balancing of chemical equations. Here one has to apply conservation of each atomic constituent in the participating molecules. Two examples are included in Fig. 9. In example I, the atoms of the water molecule

become separated and the coefficients are equal to one. All students arrived at this conclusion, and explained it in terms of the available atoms. Example II is much more difficult in that four steps of reasoning are needed, one for conservation of each atomic species. None of the students answered it correctly, and only three referred to the balance of one or two specific elements; the others said that they guessed or merely asserted that the equation was balanced. I conclude, therefore that the need to keep track of the four atomic species demanded a systematic overall approach and lack of premature closure[3] that are characteristic of formal rather than concrete thought.

Actually, both problems in Fig. 9 can be solved by an algorithm, by stating the conservation of each atomic species in the form of an algebraic equation, and then solving the resulting equations. In case I, the result is three equations for calcium, hydrogen, and oxygen, that can be solved in sequence. In case II, the result is four equations (for hydrogen, X, Z, and oxygen) and two of these have to be solved simultaneously. From my knowledge of high school courses, I believe that this algorithm is not taught, and that students balance equations by inspection and a trial-and-error process, achieving closure immediately after each trial.

Still another task involving the manipulation of chemical symbols is presented in Fig. 10. Here the student has to determine how the third reaction can be represented as a composite of the other two, and then use the composition relationship to compute the required heat of reaction. Seven out of eleven students were able to do this; the other four put the two reactions together but did not apply the factors for the molecular ratios involved. Did this task require formal thought? Associating a reaction energy with each process and operating mathematically on these energies would seem to be a formal operation. Yet the class had practiced extensively on this type of problem, though the particular example was novel. What do you think? Regardless of operational level, it may be reassuring to the teachers among you to find out that some students can learn something!

The next example involves application of the kinetic theory of gases, a powerful model for understanding chemical and thermal phenomena (Fig. 11). Complete understanding of this model certainly requires formal thought, expecially insofar as the particles of the model have idealized properties rather than being "ball bearings". In the problems of Fig. 11 only the motion of the particles is involved. Item I needs only quantitative serial ordering, but does require two inversions from the data given (high weight ↔ slow rate and slow rate ↔ long time) to the ultimate result of a direct correspondence (low weight ↔ short time, high weight ↔ long time). Eleven out of thirteen students selected answer A successfully and quoted the information given to eliminate the other choices. Only three of the students, however, gave evidence of formal reasoning by selecting the correct answer B in item II, and justifying it through the inverse square-root relationship. Most of the others took answer A, applying the inverse proportion without taking the square root, a concrete approach; a few guessed various answers. As in the biological example on microscope magnification, we find that the non-linear function is much more challenging for the students than the direct proportion.

My last example in Fig, 12 comes from high school physics.[7] Even though I have not had an opportunity to use it with students, I am presenting it because it very nicely illustrates how early and delayed closure[3] are related to concrete and formal thought. To solve the problem, the respondent has to know that the material on the right of the bimetallic strip expands more than the material on the left, and he has to be able to interpret the graph. Yet there are two ways of proceeding. In the first method (concrete operations), each alternative is tested in order and closure is achieved when the choice is either accepted or rejected. In the second method (formal operations), the overall pattern of the graph is first used to infer that metals with higher numbers expand more, so that lack of closure with respect to the original question is accepted. The final answer is then found very quickly, however, by looking for the combination with the higher-numbered material on the right side (choice C).

I hope you have found these analyses and comparisons interesting. My most important message is that concrete and formal thought may be revealed by the method an individual uses to solve a problem. The answer itself indicates the level of reasoning only rarely. I believe it would be very worthwhile for teachers to use few questions on their tests and to require explanations. This approach would provide valuable diagnostic information and feedback for the teacher, even though it would not be so suitable for rank-ordering the students according to their achievement.

I am indebted to Messrs. Gene R. Ala, Joseph Reitz, and Joseph E. Davis, and to their students at Campolindo High School, Moraga, California, for assistance in preparing this paper.

1. Science Curriculum Improvement Study, <u>Subsystems and Variables</u> Student manual, Chicago: Rand McNally & Co., 1970, page 27.

2. Science Curriculum Improvement Study, <u>Models: Electric and Magnetic Interactions</u> Student Manual, Chicago: Rand McNally & Co. 1971, page 21.

3. Eric A. Lunzer, <u>The Need For and Neglect of Research in Formal Operations</u> (this volume).

4. Science Curriculum Improvement Study, <u>Relative Position and Motion</u>, Student Manual, Chicago; Rand McNally & Co., 1972, page 38.

5. Science Curriculum Improvement Study, <u>Energy Sources</u> Student Manual, Chicago: Rand McNally & Co., 1971, page 24.

6. Anton E. Lawson and John W. Renner, private communication.

7. <u>College Board Achievement Tests</u>, 1972-73, Princeton, N.J.: College Entrance Examination Board, 1971, 1972.

8. Biological Sciences Curriculum Study, <u>Biological Science--from Molecule to Man</u> (Blue Version), Boston: Houghton Mifflin Co., 1963, Chapters 15 and 18.

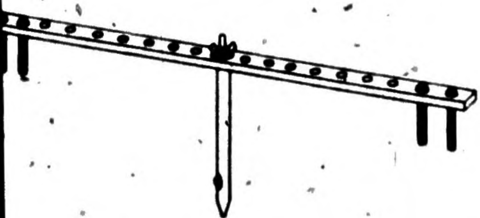
9. In my opinion, application of a two-to-one ratio does not indicate formal thought; see Warren Wollman and Robert Karplus, "Intellectual Development Beyond Elementary School V: Using Ratio in Differing Tasks," Lawrence Hall of Science, University of California, Berkeley, 1973.

FIGURE 1

Brain Teasers Date ____________________

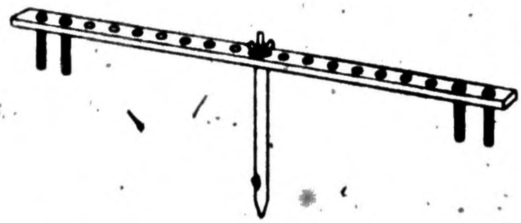
Predict which arm will make more turns.

C. One twist of the rubber band



How many turns? ____________

D. Three twists of the rubber band

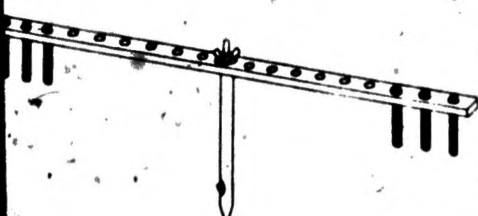


How many turns? ____________

Which variable is different? ______________________________

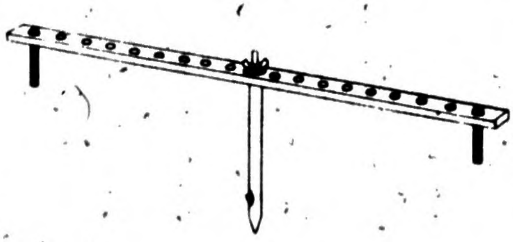
Predict which arm will make more turns.

E. Two twists of the rubber band



How many turns? ____________

F. Two twists of the rubber band



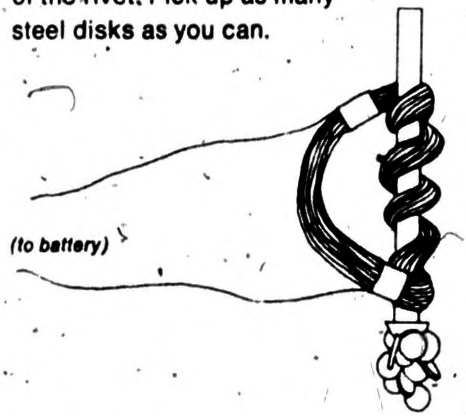
How many turns? ____________

Which variable is different? ______________________________

FIGURE 2

How does the number of turns affect the interaction of your coil-rivet system?

A. Push the coil against the head of the rivet. Pick up as many steel disks as you can.



Record the number of disks you can pick up.

1 turn ______ ______ ______

2 turns ______ ______ ______

3 turns ______ ______ ______

4 turns ______ ______ ______

5 turns ______ ______ ______

6 turns ______ ______ ______

7 turns ______ ______ ______

To put many turns on your rivet, push them tightly together. Put as many turns on the rivet as you can.

B. Investigate other variables of the coi system. Name the variables. Draw a picture and describe what you find o

FIGURE 3

Brain Teaser

Paul and Bill were pacing distances.

Here are Paul's paces:

Paul counted 15 paces from the flagpole to the water fountain.

Bill counted 20 paces from the flagpole to the water fountain.

Which are Bill's paces?

Circle A, B, or C.

A 

B 

C 

Explain your choice. ____

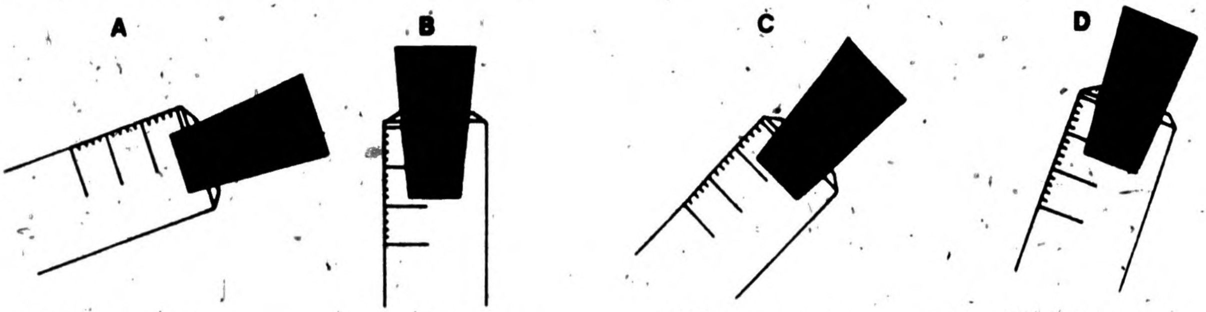
____

____

FIGURE 4

Brain Teaser

Compare these four experiments.



20 degree angle | 90 degree angle | 40 degree angle | 70 degree angle

Which stopper will receive the greatest amount of energy?

Explain your answer.

Which stopper will land at the greatest distance from the ramp?

Explain your answer.

Figure 5

I. One pair of alleles (D and d) controls a certain trait in fruit flies. When many crosses are made between Dd and dd flies, how many different genotypes will there be among the offspring, and what will be the approximate percentage of each?

II. A certain characteristic of sexually-reproducing organisms in a population is determined by one pair of alleles (A and a). The dominant allele makes up 30% of all the alleles in this population.

A. How many different genotypes are there with respect to this characteristic?
What percentage of each is present in the population?

B. How many different phenotypes are there with respect to this characteristic?
What percentage of each is present in the population?

solution to I:

	D	d
d	Dd	dd
d	Dd	dd

solution to II:

	A A A	a a a a a a a
A A A	9 AA	21 Aa
a a a a a a a	21 Aa	49 aa

FIGURE 6

WHICH OF THE FOLLOWING IS THE BEST EXAMPLE OF A FOOD CHAIN?

A. SPARROW → SEEDS → HAWK → BACTERIA
B. SEEDS → BACTERIA → SPARROW → HAWK
C. SEEDS → SPARROW → HAWK → BACTERIA
D. BACTERIA → SEEDS → SPARROW → HAWK

PLEASE EXPLAIN WHAT IS WRONG WITH EACH ITEM YOU DID NOT CHOOSE.

FIGURE 7

A MICROSCOPE HAS OBJECTIVE LENSES OF 10X AND 50X POWER. UNDER HIGH POWER, 80 EVENLY DISTRIBUTED BACTERIAL CELLS CAN BE SEEN IN THE FIELD OF VIEW. ABOUT HOW MANY CELLS CAN BE SEEN IN THE FIELD OF VIEW UNDER LOW POWER ON THE SAME SLIDE?

A. 3
B. 16
C. 30
D. 400
E. 2000

PLEASE EXPLAIN HOW YOU FOUND THE ANSWER.

FIGURE 8

HOW MANY ATØMS ARE IN ONE MOLECULE OF THE SUBSTANCE

$(NH_4)_2TiO(C_4O_4)_2 \quad H_2O$?

PLEASE SHOW YOUR CALCULATION.

FIGURE 9

I. BALANCE THIS CHEMICAL REACTION:

1 CA + (A) $H_2O \rightarrow$ (B) CAO + (C) H_2

THE COEFFICIENT (A) IS

A. 1 B. 2 C. 3 D. 4 E. 5

PLEASE EXPLAIN YOUR CHOICE.

II. BALANCE THIS EQUATION INVOLVING THE NEW ELEMENTS X AND Z:

2 H_2XO_3 + (A) $H_3ZO_3 \rightarrow$ (B) HX + (C) H_3ZO_4 + (D) H_2O

THE COEFFICIENT (C) IS

A. 1 B. 2 C. 3 D. 4 E. 5

PLEASE EXPLAIN YOUR CHOICE.

FIGURE 10

CONSIDER THE REACTIONS

$$2\,Fe + (3/2)O_2 \rightarrow Fe_2O_3 \qquad \Delta H = -191 \text{ kcal}$$

$$3\,Fe + 2\,O_2 \rightarrow Fe_3O_4 \qquad \Delta H = -266 \text{ kcal}$$

FROM THIS INFORMATION, CALCULATE THE H OF THE REACTION

$$2\,Fe_3O_4 + (1/2)O_2 \rightarrow 3Fe_2O_3 \;,\; \Delta H = \underline{\qquad\qquad}$$

PLEASE EXPLAIN HOW YOU FOUND THE ANSWER.

FIGURE 11

I. ACCORDING TO THE KINETIC THEORY, THE RATE OF DIFFUSION OF A HIGH MOLECULAR WEIGHT GAS IS SLOWER THAN THE RATE OF DIFFUSION OF A LOW MOLECULAR WEIGHT GAS. WHICH OF THE FOLLOWING CAN YOU CONCLUDE?

A. PERFUME VAPOR WITH A MOLECULAR WEIGHT OF 360 CAN BE SMELLED BEFORE ONION VAPOR WITH A MOLECULAR WEIGHT OF 720.

B. THE HIGHER THE MOLECULAR WEIGHT OF A GAS, THE SOONER AN EQUILIBRIUM STATE IS REACHED IN A CLOSED SYSTEM.

C. ONION VAPOR IS MORE OFFENSIVE THAN PERFUME VAPOR.

D. PERFUME VAPOR WITH A MOLECULAR WEIGHT OF 360 WILL BE SMELLED AFTER ONION VAPOR WITH A MOLECULAR WEIGHT OF 720.

PLEASE EXPLAIN BRIEFLY WHAT IS WRONG WITH THE OTHER CHOICES.

II. MORE PRECISELY, THE RELATIVE RATES OF DIFFUSION OF TWO GASES UNDER IDEAL CONDITIONS ARE INVERSELY PROPORTIONAL TO THE SQUARE ROOTS OF THEIR MOLECULAR WEIGHTS. IN A TEST COMPARING DIFFUSION OF ONION VAPOR (MOLECULAR WEIGHT 720) AND PERFUME VAPOR (MOLECULAR WEIGHT 360), THE ONION VAPOR IS DETECTED ABOUT SIX SECONDS AFTER ITS RELEASE. HOW LONG AFTER RELEASE WOULD YOU EXPECT PERFUME VAPOR TO BE DETECTED?

A. 3 SECONDS B. 4 SECONDS C. 6 SECONDS D. 9 SECONDS E. 12 SECONDS

PLEASE EXPLAIN HOW YOU FOUND THE ANSWER.

FIGURE 12

LINEAR SPECIMENS OF FIVE DIFFERENT MATERIALS, EACH OF THE SAME LENGTH AT 0°C, ARE HEATED SLOWLY; THE EFFECTS OF TEMPERATURE CHANGES ON LENGTHS ARE SHOWN IN THE GRAPH. WHEN RIVETED TOGETHER TO FORM A BIMETALLIC ELEMENT FOR A THERMOSTAT, WHICH COMBINATION OF TWO MATERIALS WOULD CAUSE THE ELEMENT TO CURVE AS SHOWN WHEN THE TEMPERATURE IS INCREASED?

A. 2 ON THE LEFT, 1 ON THE RIGHT
B. 3 ON THE LEFT, 1 ON THE RIGHT
C. 3 ON THE LEFT, 5 ON THE RIGHT
D. 4 ON THE LEFT, 2 ON THE RIGHT
E. 5 ON THE LEFT, 4 ON THE RIGHT

PLEASE EXPLAIN WHAT IS WRONG WITH THE OTHER CHOICES.